Oscillatory decay of magnetization induced by domain-wall stray fields

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INTRODUCTION

A simple structure of a magnetic random access memory (MAGRAM) cell consists of two magnetic layers whose relative magnetization directions can be changed from parallel (e.g. "0") to antiparallel (e.g. "1") by a small magnetic field. In principle, this can be done by using a "soft" and a "hard" magnetic layer separated by a non-magnetic spacer layer. In such a structure the magnetization direction in the hard layer is unaffected by a small (less than 50 Oe) external magnetic field and only the magnetization direction in the soft layer is changed. In practice, however, it has been observed that such a device is unstable and ceases to function properly when the soft layer is cycled many times. Although the applied external magnetic field is sufficiently small a demagnetization of the hard layer occurs. This demagnetization process has been argued to be caused by dipolar fields originating from domain-walls in the soft layer which form during the switching process. To be able to investigate this demagnetization phenomenon a technique is required which is capable to access individually the magnetic properties of the hard and the soft magnetic layer. This can be achieved by using (soft) x-ray magnetic circular dichroism (XMCD) spectroscopy as contrast mechanism in photoelectron emission microscopy (PEEM) [1] which allows to study locally resolved the magnetization of each layer.

EXPERIMENT

The studied magnetic trilayer of 100 Å $Co_{84}Fe_{16}$/15 Å Cr/50 Å $Co_{75}Pt_{12}Cr_{13}$ (soft/spacer/hard) was grown by dc magnetron sputtering in 10^{-3} Torr Ar on Si/SiO_2 wafers [2], and the sample was capped with 15 Å Al to prevent oxidation. The hard magnetic layer was grown on top of the structure to make it accessible for PEEM, which detects secondary electrons produced during absorption of x-rays, and so is surface sensitive. The microscopy studies were carried out with the PEEM-II microscope at the Advanced Light Source in Berkeley, using 80% circularly polarized soft x-rays from the bending magnet source 7.3.1.1. XMCD-PEEM images were recorded at the Co $L_{2,3}$ absorption edges with the projection of the photon spin aligned along a particular direction, that of the initial macroscopic magnetization of the sample, and the direction of the applied field. The contrast was enhanced by dividing images obtained at the L_3 and L_2 edges. Note that the Co signal is purely due to the hard magnetic layer as the 1/e sampling depth in transition metals at these photon energies is only about 20 Å. Moreover, no signal from the soft CoFe layer was observed at the Fe L edges.

RESULTS

Fig. 1 shows PEEM images of the same 10 x 11 μm^2 area of the hard magnetic film of the trilayer structure. The structure has first been prepared in a fully magnetized remanent state in an external field of 5 kOe which here would correspond to an uniformly black PEEM image (not shown). The magnetization of the soft magnetic layer has then been cycled in an external field of ±200 Oe (applied in-situ) which is an order of magnitude smaller than the coercivity of the hard magnetic layer. The four images show the hard layer after N_c =1, 5, 50 and 300 cylces. As N_c increases, regions with reversed magnetization (white areas) progressively expand. After about 50 cycles, the proportion of black and white regions is approximately the same. However, even though the net magnetization is close to zero, the magnetic state of the film continues to evolve

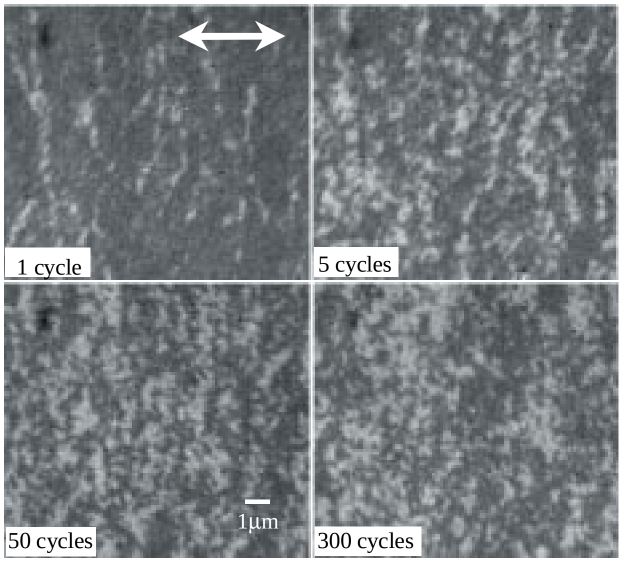

Figure 1. PEEM images of a 10 x 11 μm^2 area of a CoPtCr layer of a CoPtCr/Cr/CoFe sandwich recorded at the indicated numbers of cycles of the field used to reverse the moment of the soft CoFe layer. The white arrow indicates the cycling field direction. Black and white areas correspond to the two orientations of the magnetization component parallel to the cycling field direction

with further field cycling. As shown in Fig. 1, the image recorded for 300 cycles is quite different from that for 50 cycles, even though the proportion of black and white regions is about the same. A particularly interesting feature of these images is the increase of disorder of the magnetization distribution with increasing N_c. For small N_c, regions with reversed magnetization appear to form strands approximately perpendicular to the net magnetization. This ordered structure is still weakly present for 50 cycles, but has vanished completely for 300 cycles.

PEEM images of a representative 5 x 5 μm^2 area of the hardmagnetic layer are shown in Fig. 2 recorded after every ½ cycle for the first 3 cycles. After the first ½ cycle (soft magnetic layer from + to -), reversed domains (white areas) appear very clearly, forming strands roughly perpendicular to the initial magnetization direction. When the soft layer is switched back to its original direction (1 cycle), only small changes are observed in the PEEM image. Indeed, the relative proportion of reversed domains tends to decrease as some of these domains have switched back to their initial orientation (see, for example, the highlighted part of the images). The next few cycles result in a similar behavior: switching the soft layer from + to – induces a large increase of reversed domains, while the reversal from – to + has a weaker impact, with a slight decrease of the overall area of reversed domains, i.e., we observe an oscillatory behavior of the magnetization decay. Note also that the shape of the reversed domains also changes. The strands of reversed magnetization tend to break into smaller domains alternating in direction.

CoPtCr films are known to have a granular structure [4]. The hard magnetic CoPt grains are surrounded by Cr-rich boundaries, which are weakly magnetic and strongly reduce exchange interactions between the CoPt grains. In the simplest model, the CoPt grains are coupled only by dipolar interactions. Note that the grain size of about 10-20 nm is not resolved by PEEM, whose resolution of about 50 nm limits us to resolve clusters of more tightly coupled grains. Whilst dipolar interactions play an important role in the magnetization process of CoPtCr films it is difficult to see how they could be responsible for the appearance of the strands of reversed magnetization shown in Fig. 1 and 2. Dipolar interactions would tend to favor the creation of reversed moment in the direction parallel rather than perpendicular to the net magnetization of the hard layer. However, perpendicular to the magnetization direction, dipolar interactions would tend to favor the anti-parallel orientation of neighboring regions. Thus, it is possible to rationalise some of the features observed in the PEEM images of Fig. 2. In particular, the breaking up of strands perpendicular to the magnetization into smaller regions with alternating magnetic orientations and the broadening of the reversed domains along the magnetization direction (see

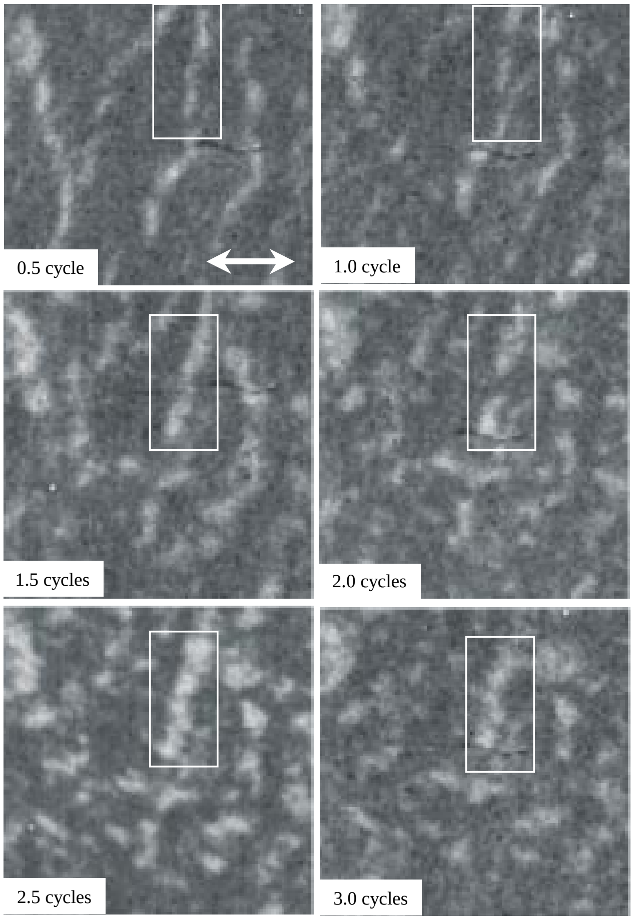

Figure 2. PEEM images of the same 5 x 5 μm^2 area recorded at the indicated numbers of cycles. The white arrow indicates the cycling field direction. The white rectangle highlights the gradual evolution of one area of the magnetization of the hard layer as the soft CoFe layer moment is cycled back and forth.

for example the highlighted part of the images recorded at 0.5, 1.5 and 2.5 cycles) may be explained on the basis of dipolar interactions. These effects can be expected as the magnetization reversal is assisted by the dipolar fields of the neighboring reversed domains.

Neither the oscillatory behavior of the magnetization decay nor the apparition of the strands of reversed domains fit a simple model of domain-wall stray field induced coupling. In particular, if only Néel domain walls with single segments are considered, the in-plane stray fields from such walls will be perpendicular, and their sign will only depend on the chirality of the wall [5]. Thus, assuming an equal distribution of Néel walls of opposite chirality in the soft layer during its magnetization reversal, the decay of the hard layer's magnetization, within this model, would not depend on the switching direction of the soft layer and would thus exhibit a simple monotonic behavior. The observation of an oscillatory behavior therefore indicates the presence of more complex domain walls like a cross-tie wall [4]. With the help of micromagnetic simulations we have been able to reproduce the observed demagnetization behavior. These simulations suggest that the oscillatory behavior is indeed related to the motion of vortices within the soft layer during its magnetization reversal as will be discussed in our forthcoming publication [5].

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